AM of High Temperature Materials for Harsh Environments

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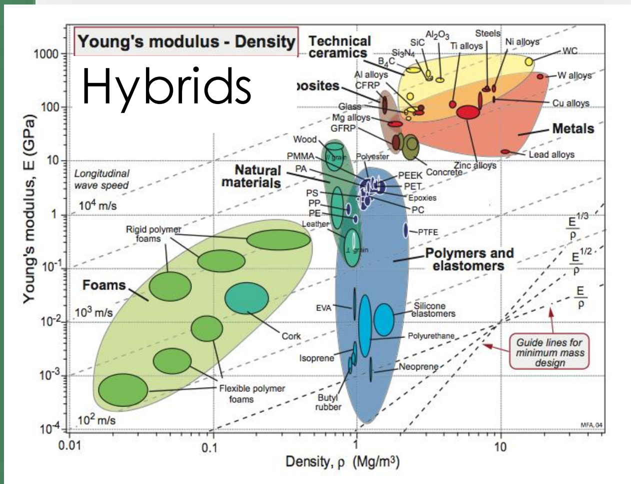
Overview

- <u>Motivation</u>
  - Q1: Why do we need additive manufacturing (AM)?
  - Q2: What are the physical processes, are they new?
  - Q3: Why is it relevant for superalloys?
- <u>Challenges</u>: Defects & Microstructural Heterogeneities
- <u>Current Directions</u>: Modeling, Make, and Measuring
- <u>Future Directions & Opportunities</u>:
  - Sire-Specific Microstructure Control
  - Refractory Alloys for Harsh Conditions Designed for AM
- <u>Summary</u>

Q1: By providing design flexibility, Additive Manufacturing is considered as the Renaissance of manufacturing



Embedded Electronics

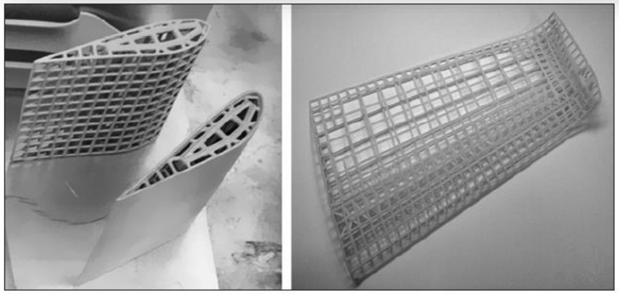


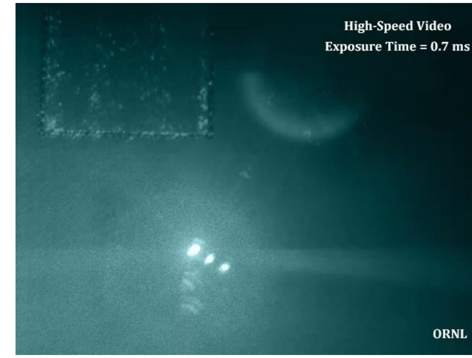
FIGURE 4 Two complex trusses suggest the difficulty of predictive analysis.

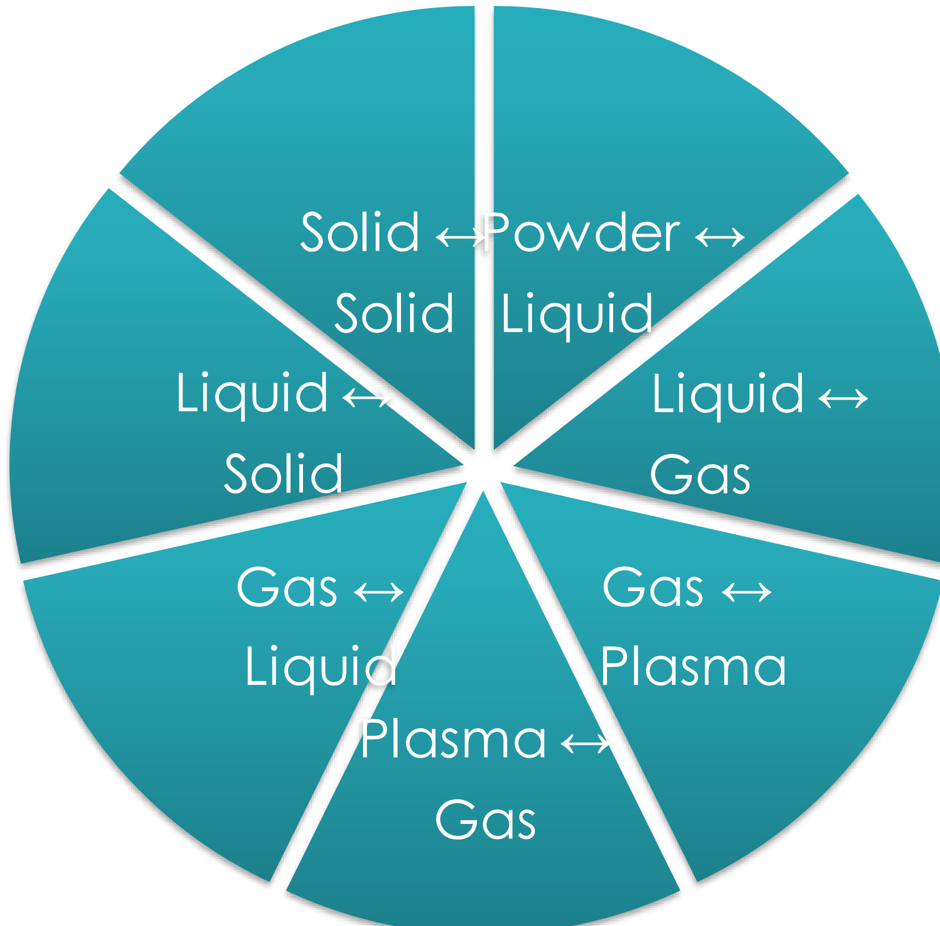
- **Today: Additive Manufacturing of Nickel Superalloys**

Q2: What are the physical processes during AM?

- Complex Geometries
- Energy Deposition
- Melting & Powder Addition
- Evaporation & Condensation
- Heat & Mass Transfer
- Solidification
- Solid-State Phase Transformation
- <u>Repeated Heating and Cooling – Thermal Gyrations</u>

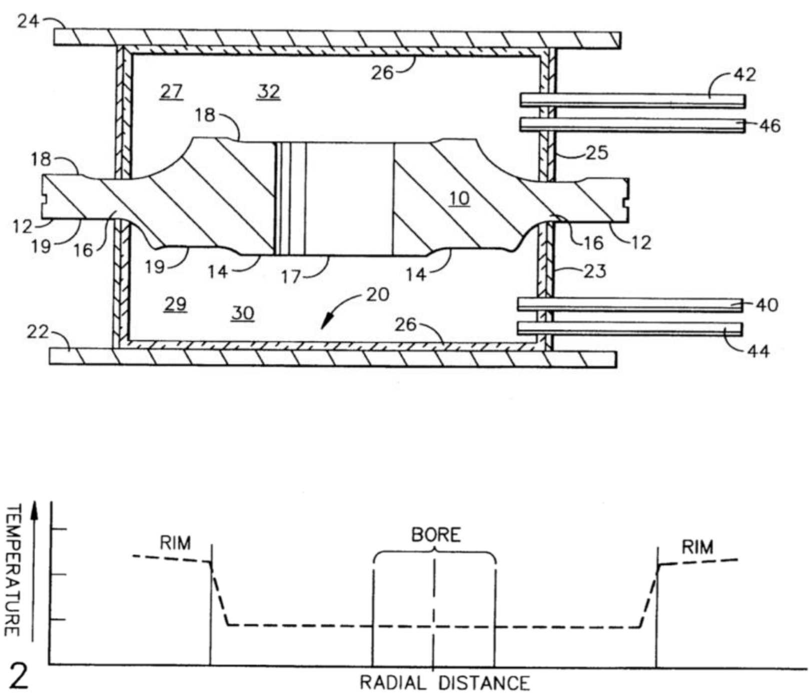
Electron Beam



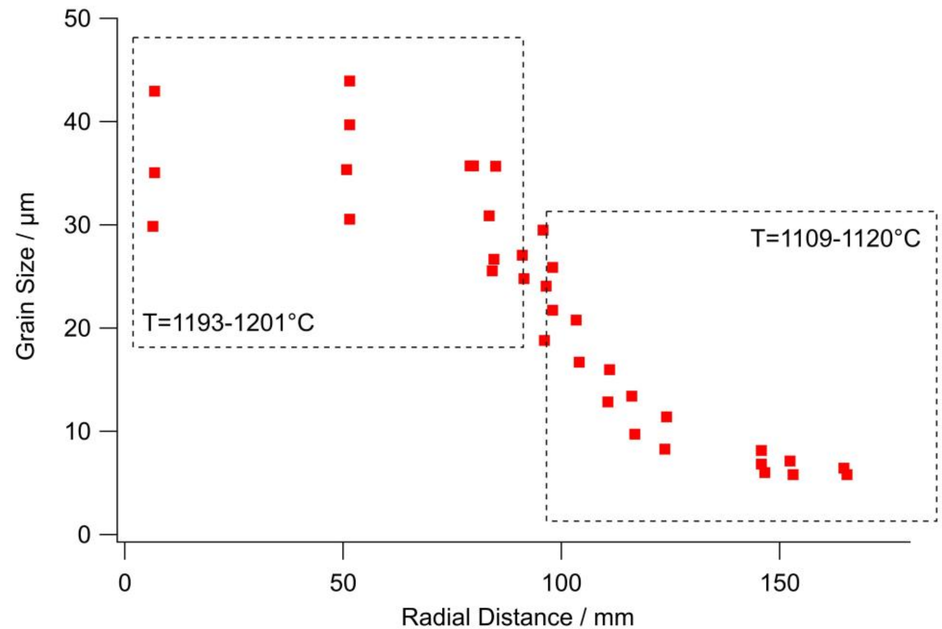


Q3: Can we use AM to arrive at complex geometries and site-specific properties?

US Patent 5,527,402, 1986



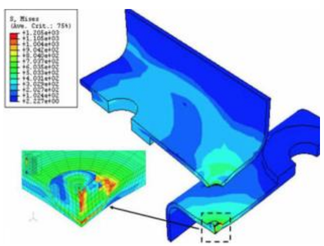
Mourer and Williams (2004)
Rene 104

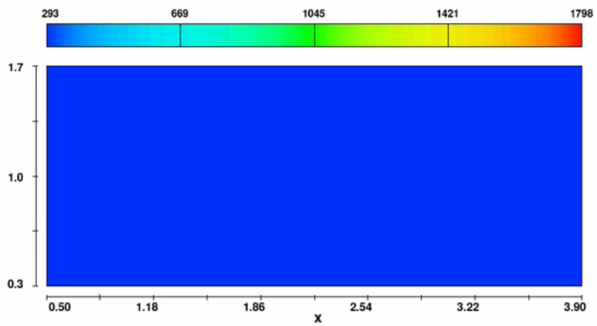


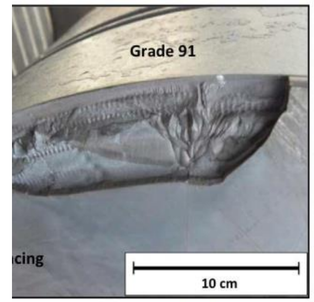
- In early 1986, GE researchers invented dual heat treatment to arrive at spatial grain structure control.

Physical processes are similar to Welding & Joining, but with complex boundary conditions…

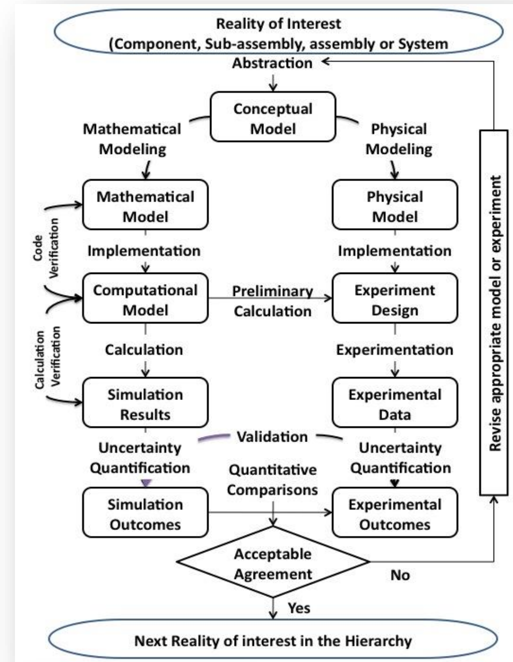
Design → **Process Selection** → **Process Controls** → **Geometrical Conformity** → **Microstructure Control** → **Qualification & Standards**

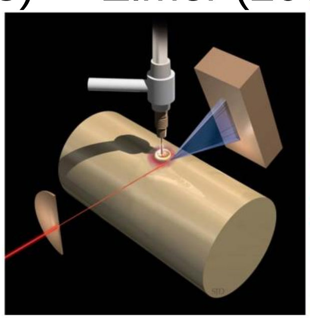


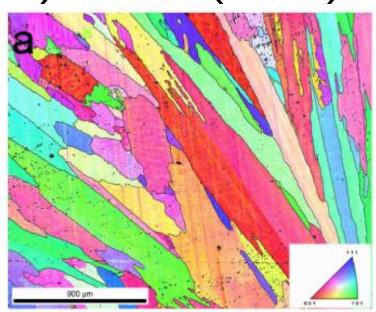


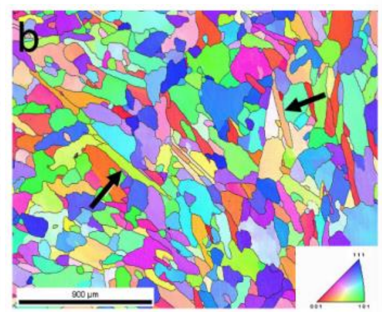


Yang (2008) Elmer (2004) Lim (2010) Lolla (2014)

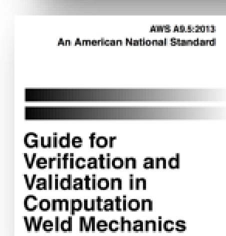








- Why is it relevant to superalloys?

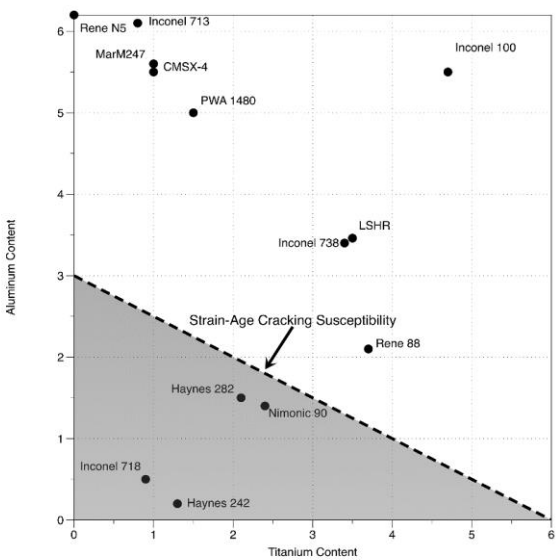

AWS A9.5:2013
An American National Standard

Guide for Verification and Validation in Computation Weld Mechanics

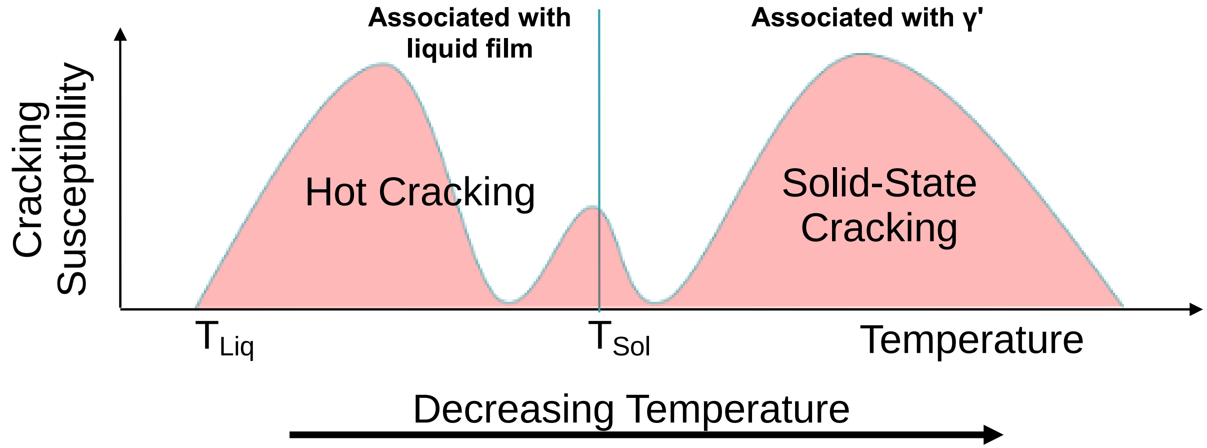
Challenges

Most Desirable Materials For Extreme and Harsh Environments are Difficult to Process: Materials Susceptible to Cracking

Weldability of Ni-base Superalloys

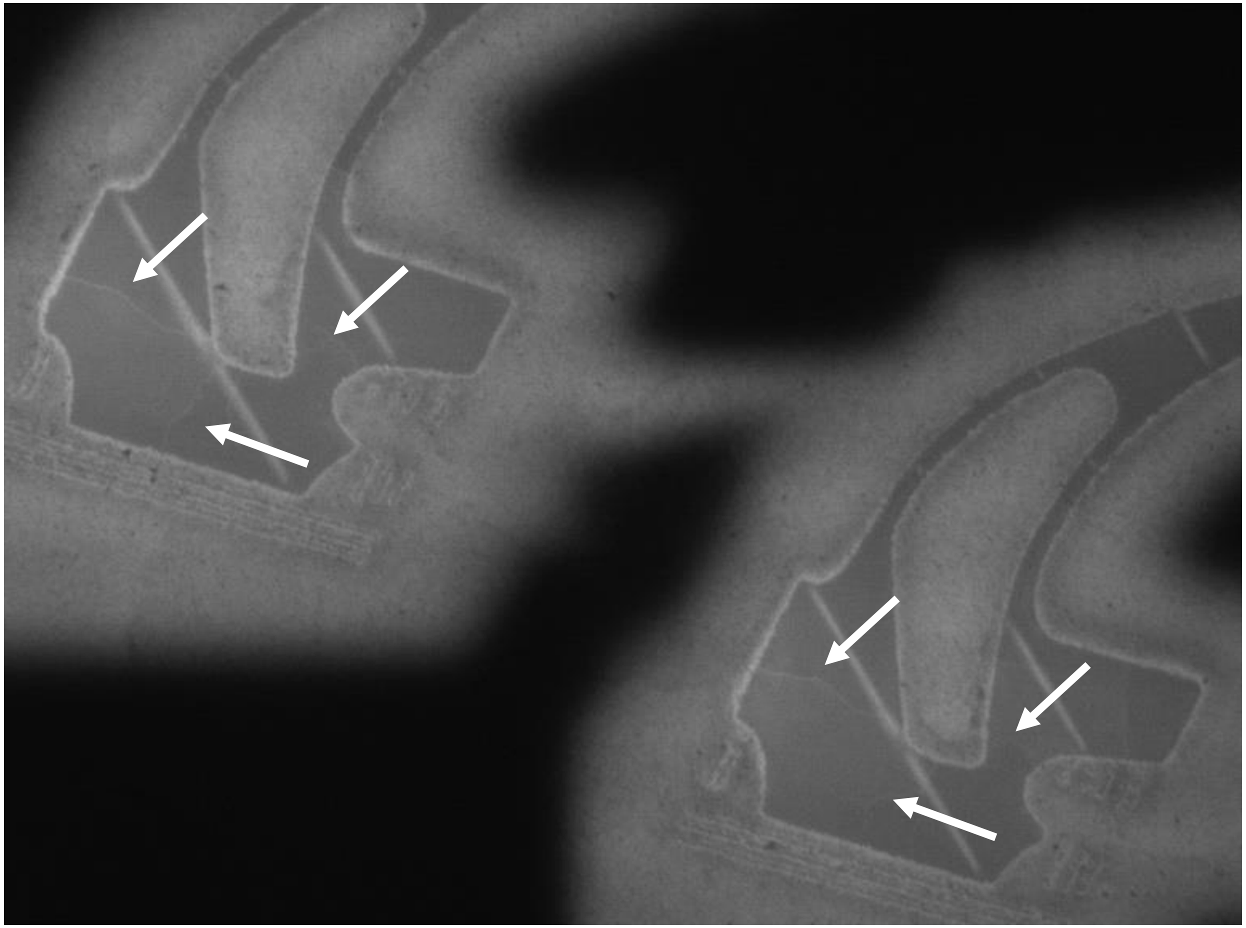


Ni-base Superalloy Cracking Mechanisms

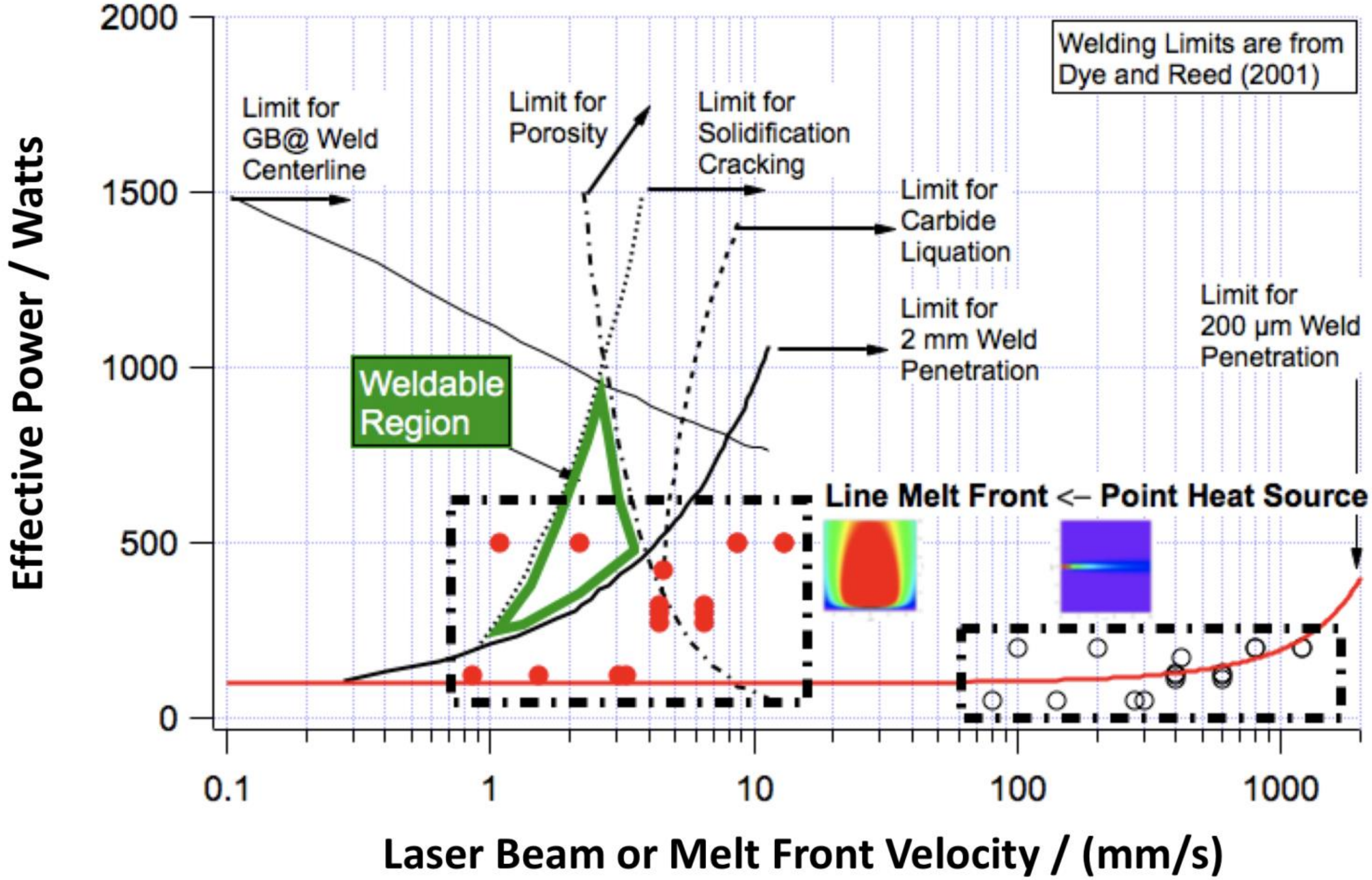


Most Desirable Materials For Extreme and Harsh Environments are Difficult to Process: Process, Geometry, and Material Linked

Crack Formation in Mar-M247



Key parameter: Movement of the weld pool, rather than the power source!



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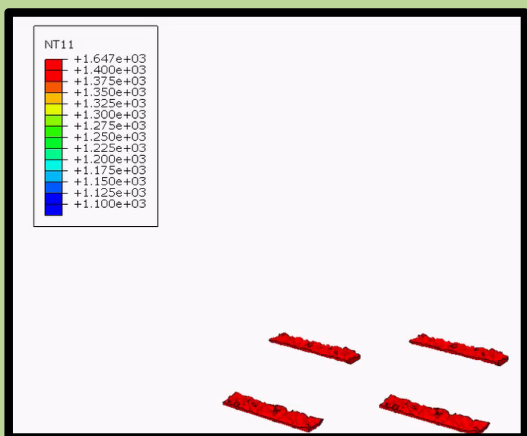
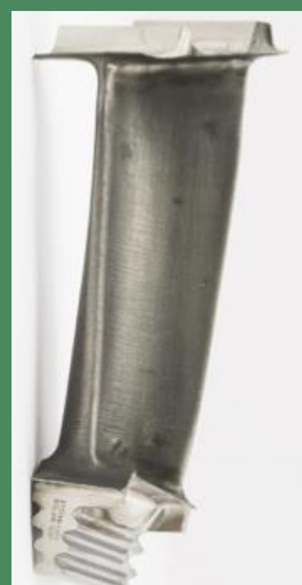
Current Directions: Inconel 738 Airfoil Case Study

Model



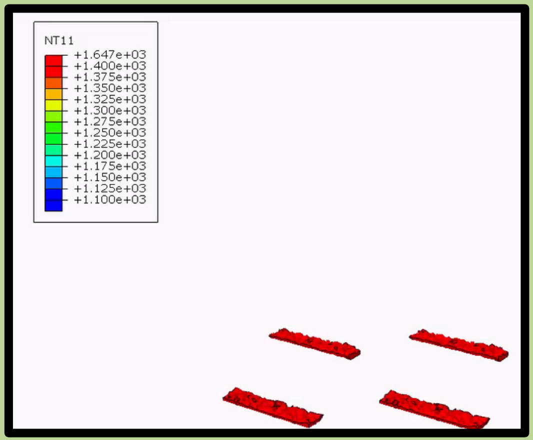
Make



Measure

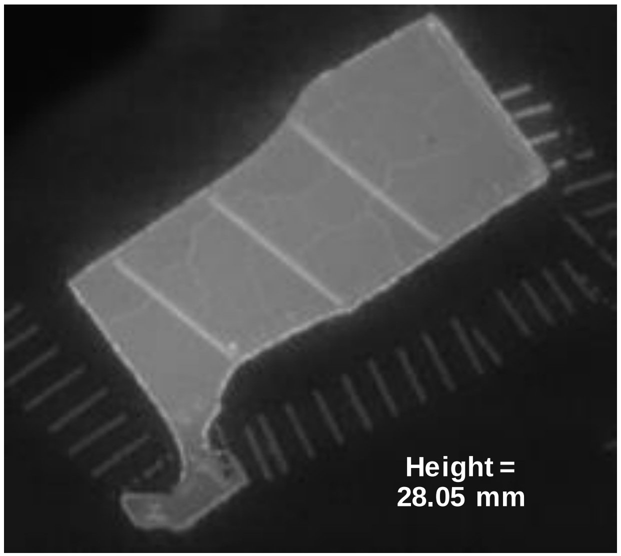
Model

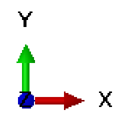
Model

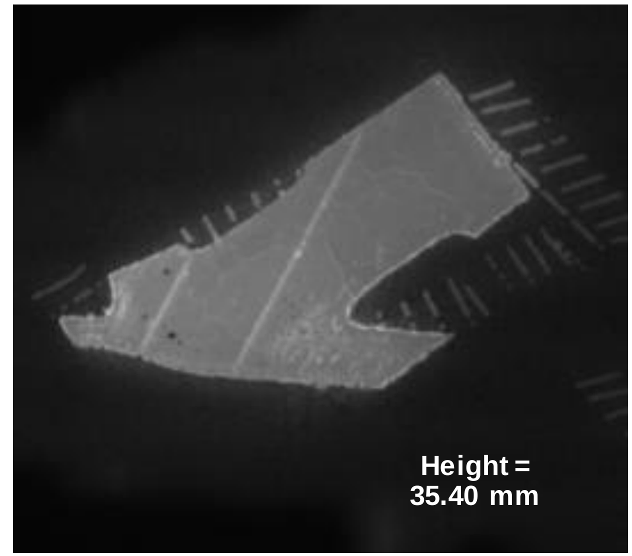

NT11
+1.647e+03
+1.400e+03
+1.375e+03
+1.350e+03
+1.325e+03
+1.300e+03
+1.275e+03
+1.250e+03
+1.225e+03
+1.200e+03
+1.175e+03
+1.150e+03
+1.125e+03
+1.100e+03

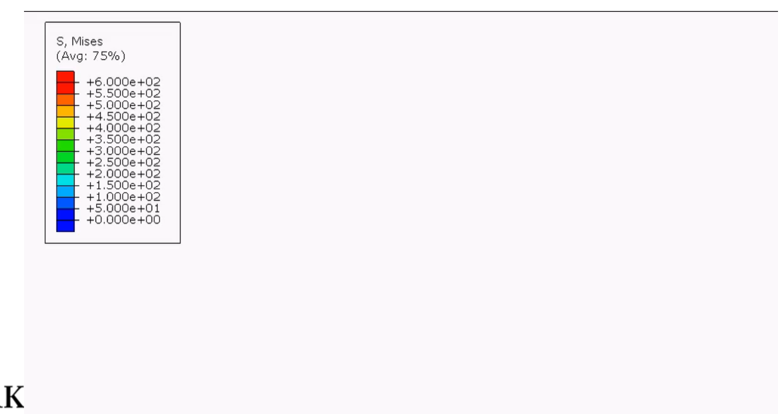
Enabling Scan Path Optimization through Computational Modeling

- Temporal and spatial distribution of cracking tendency
  - Peak tensile stress locations coincided with cracks
  - Geometry and default scan pattern interaction

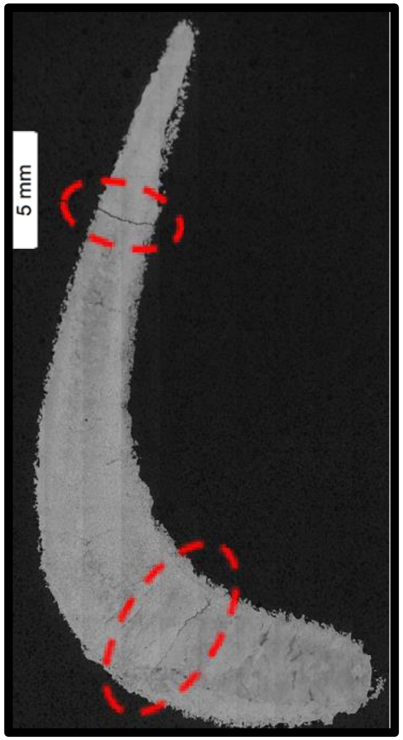




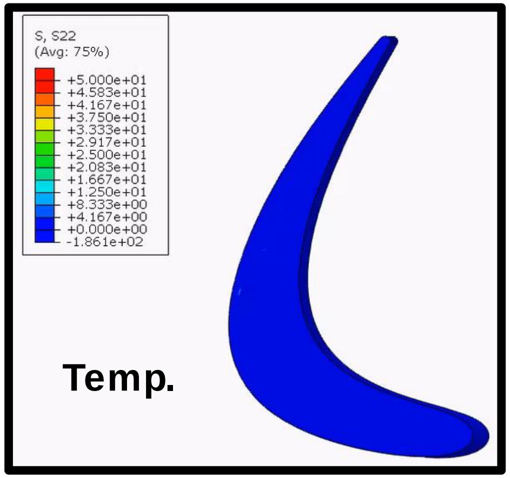


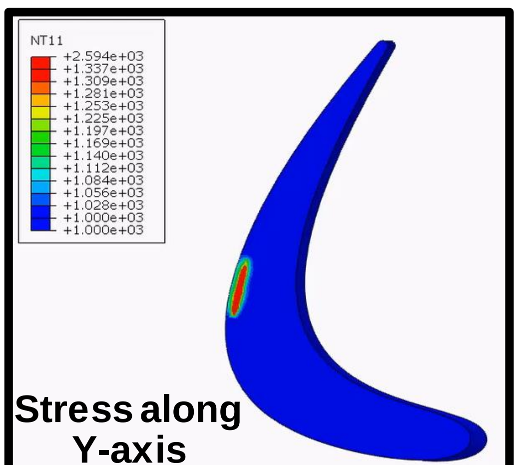


Enabling Scan Path Optimization through Computational Modeling

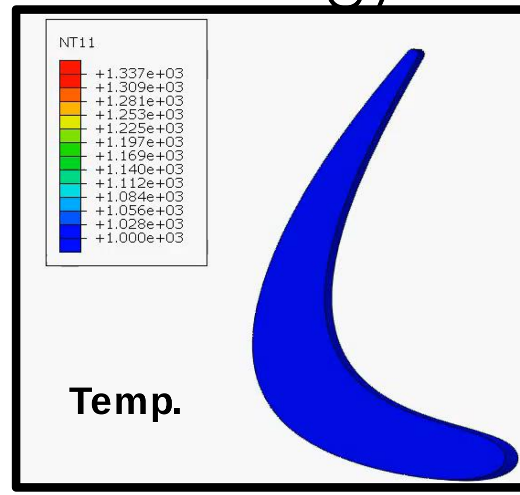


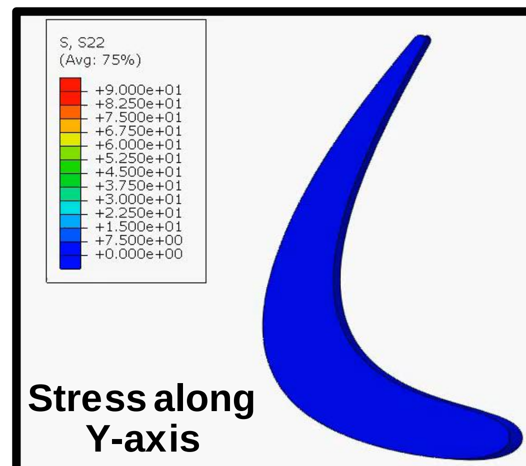
Standard Strategy





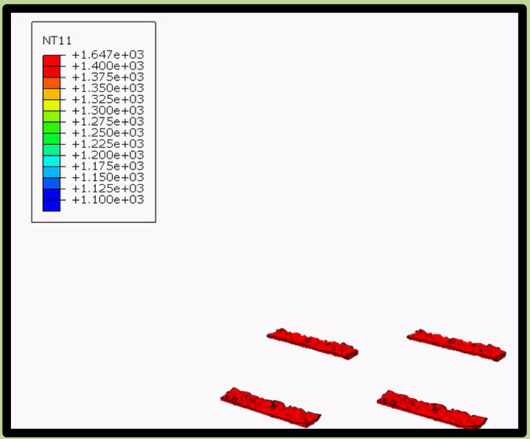
Alternative Optimized Strategy





Make

Model



Make

Manufacturing of Defect Prone Ni-base Superalloys Through by EBM

Manufacturing: Two Arcam Q10+ EBM Printers

172 Airfoils

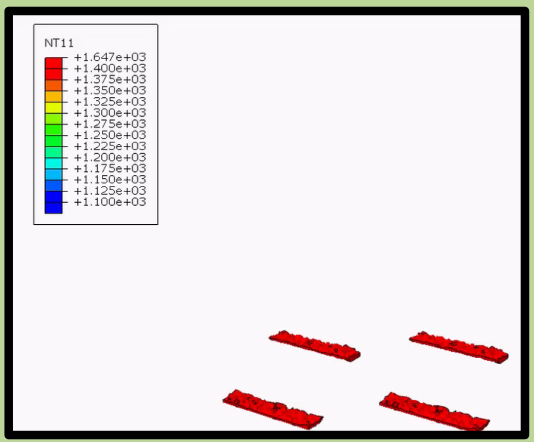
Material: Inconel 738LC (Ni-284-1)

Cr	Co	Ti	Al	Ta	W	Nb	Mo
16	8.5	3.45	3.45	1.75	2.6	0.85	1.75

1600lbs x 4 powder uses/reuses

Measure

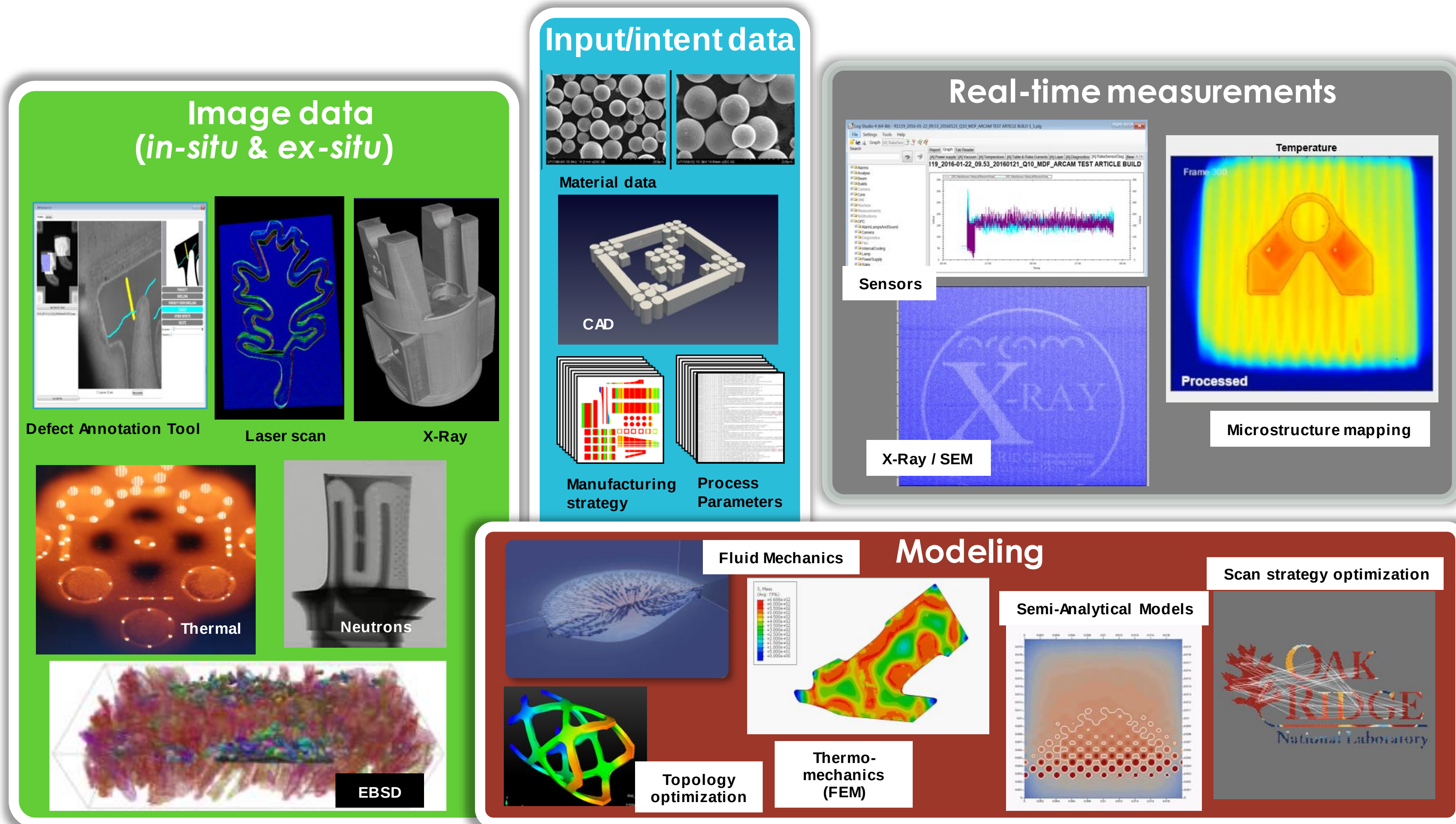
Model



Make

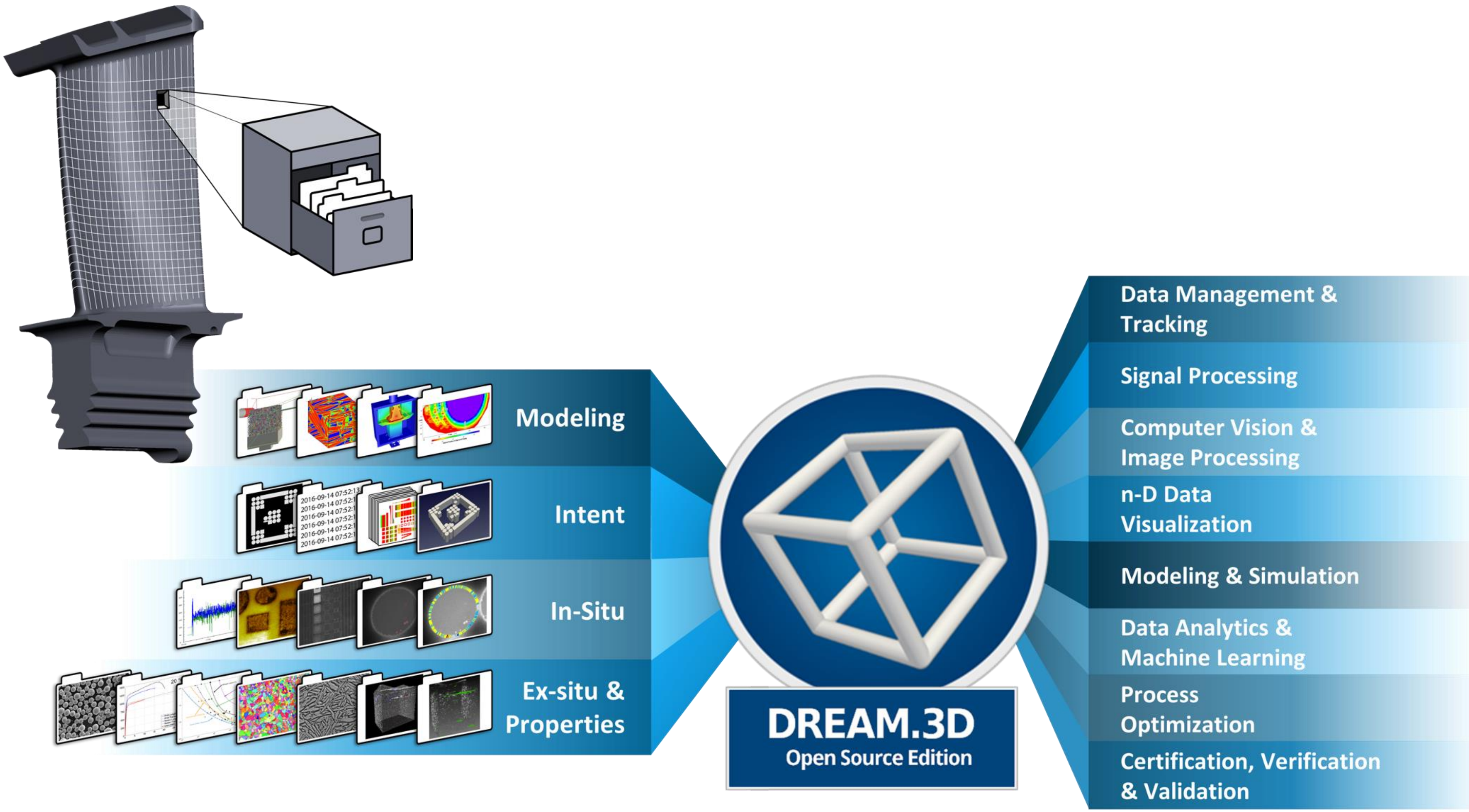
Measure

What are the Available Data Streams

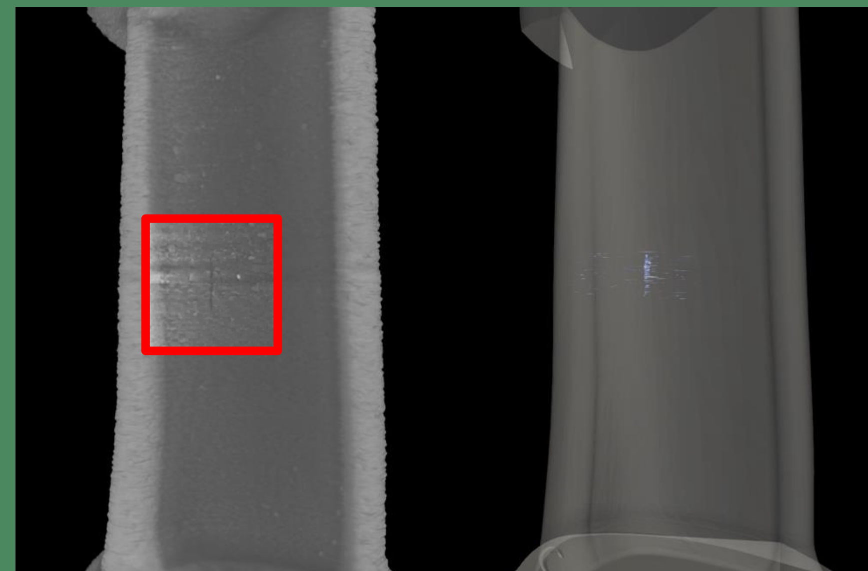


Driving the Next Materials Revolution

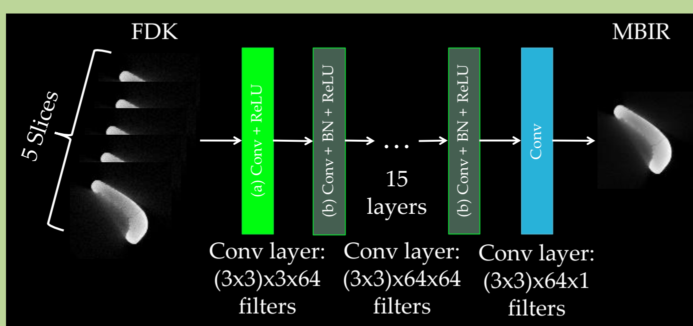
Creating a Framework for Coupling Data Analytics with Advanced Manufacturing



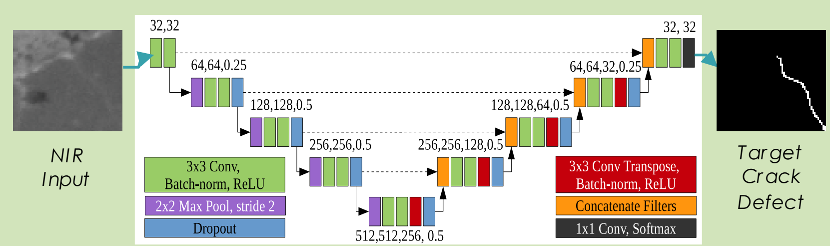
AI for CT Reconstruction and Defect Detection



ANN For CT Data Reconstruction



AI/ML for Defect Detection



U-Net Architecture

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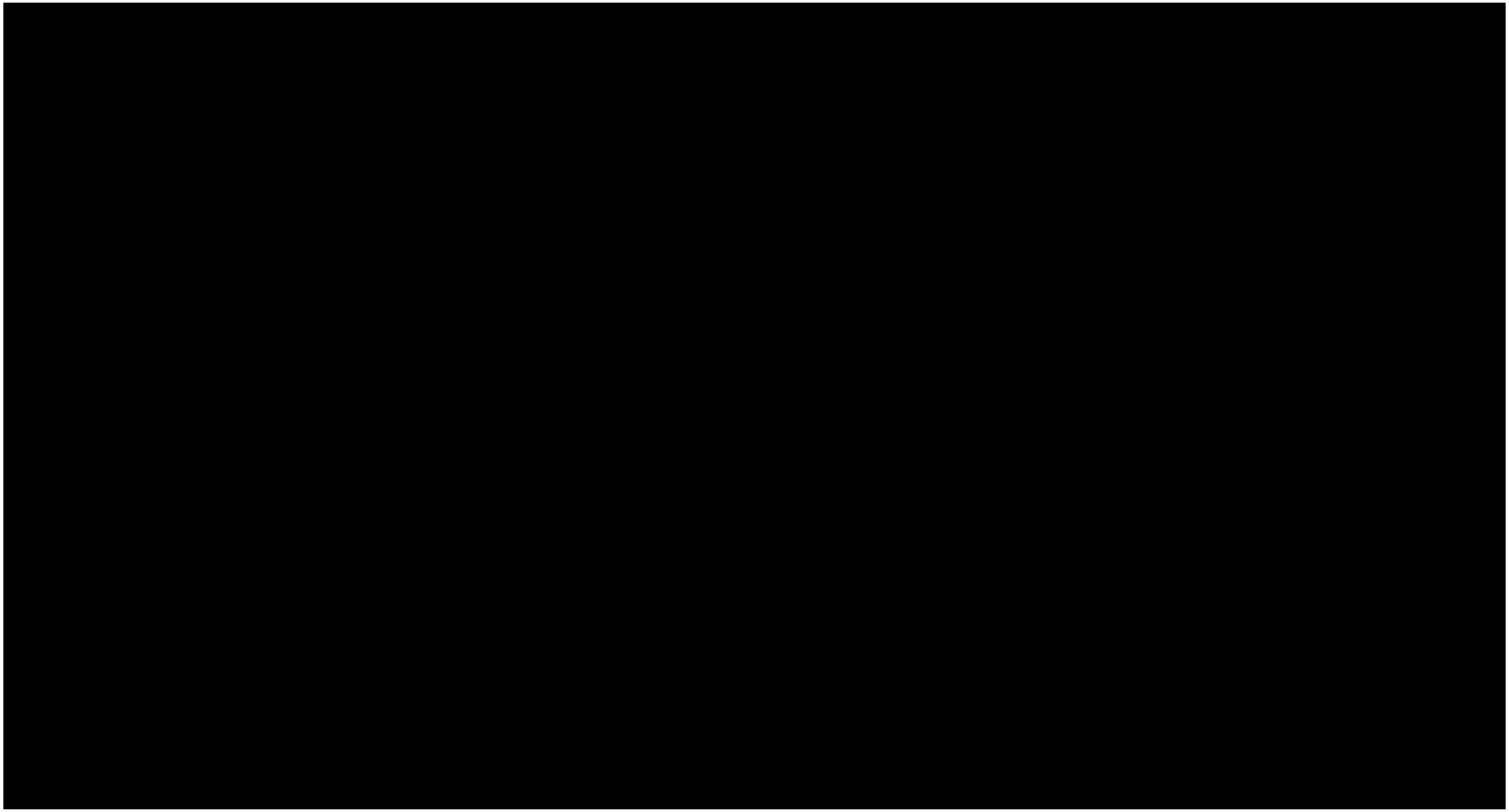
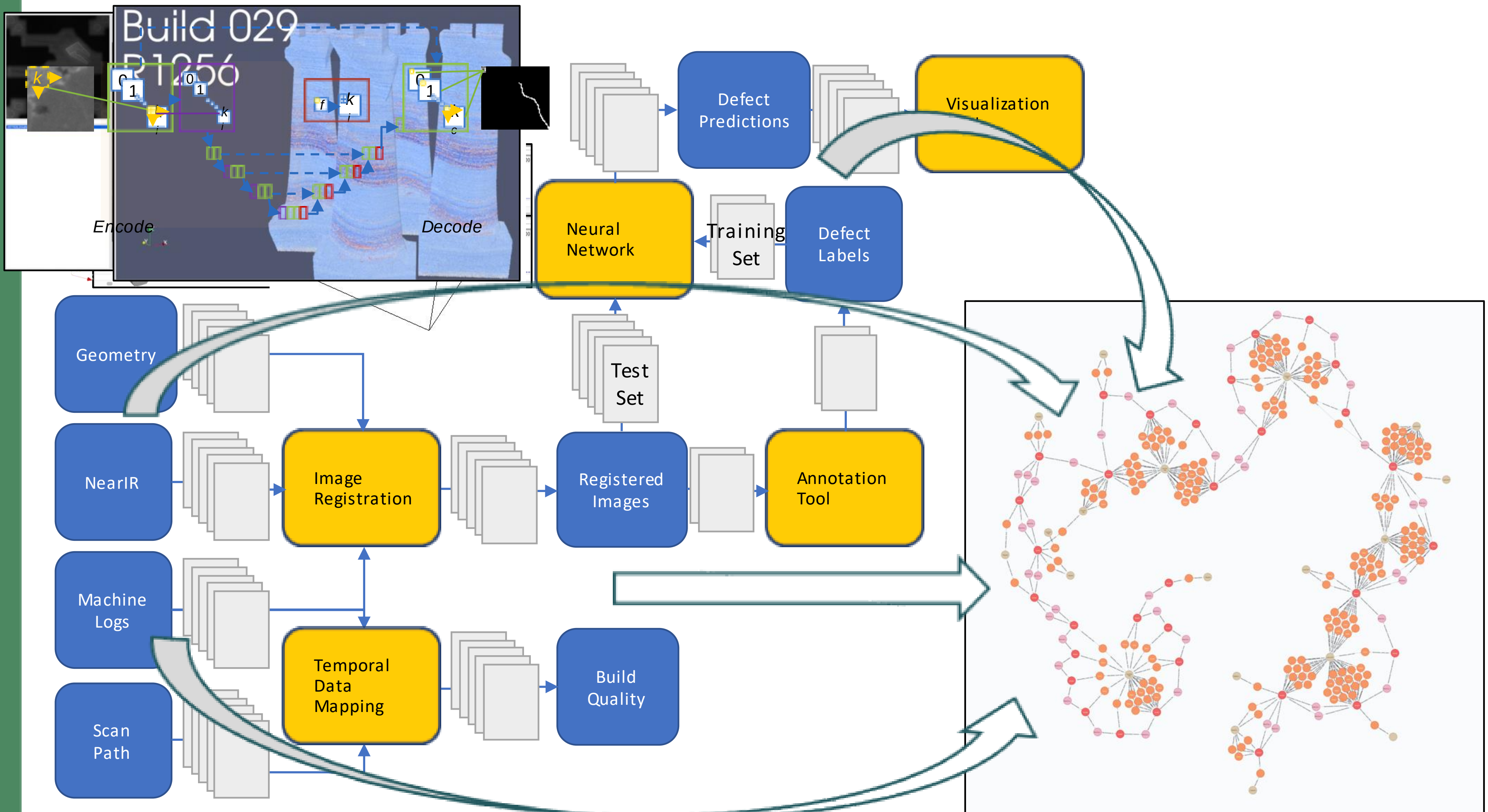
Fuse Intent and Sensor Data to Begin Creating Digital Twins



Merging and Managing of Data Streams



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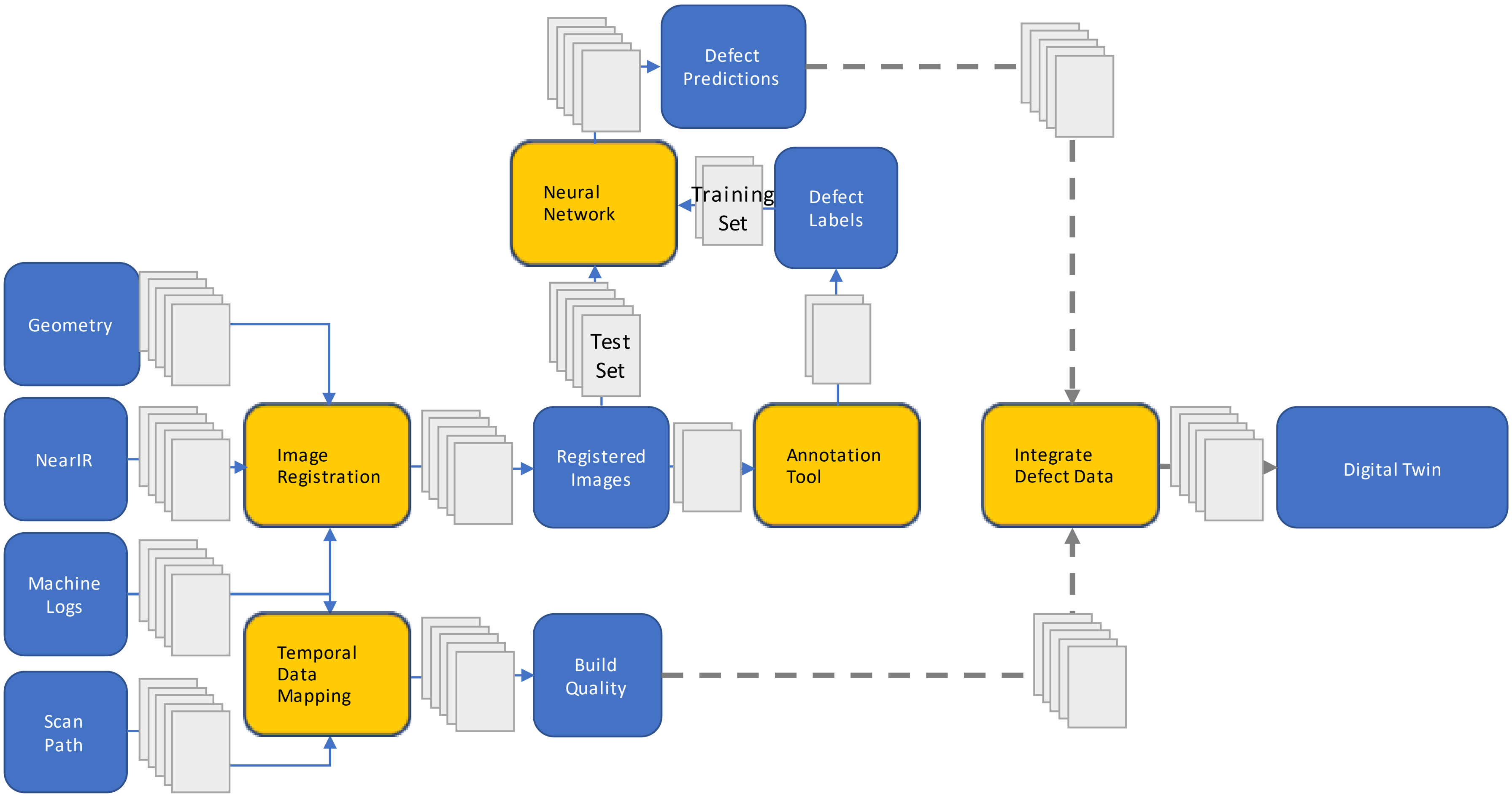
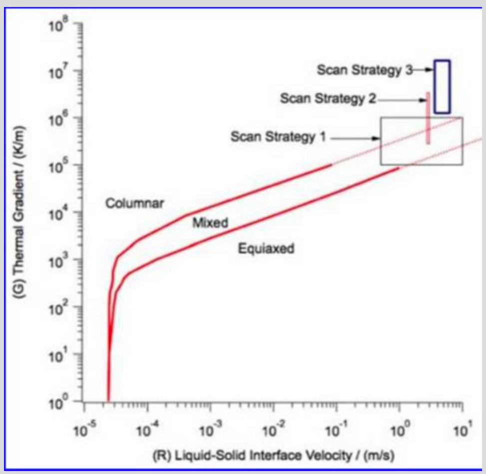
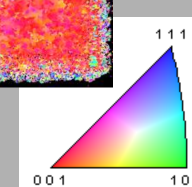
Merging and Managing of Data Streams



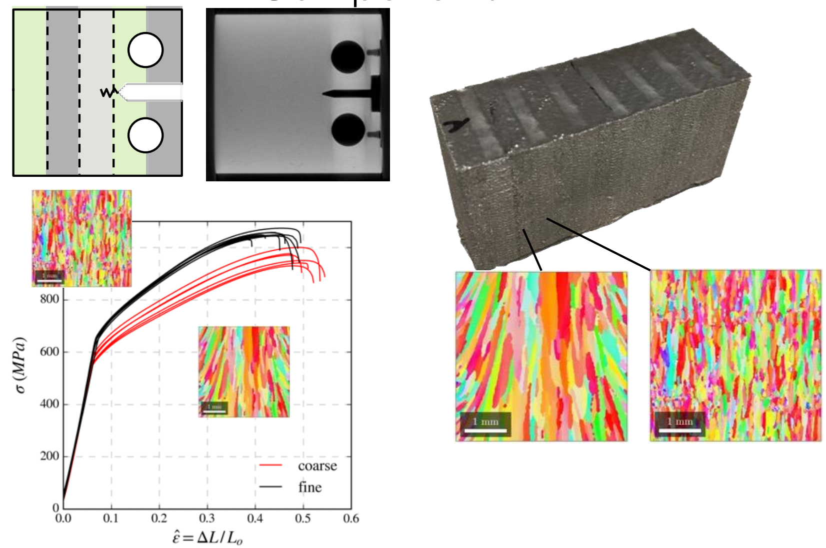
Opportunities: Data Driven Microstructures and Alloy Design



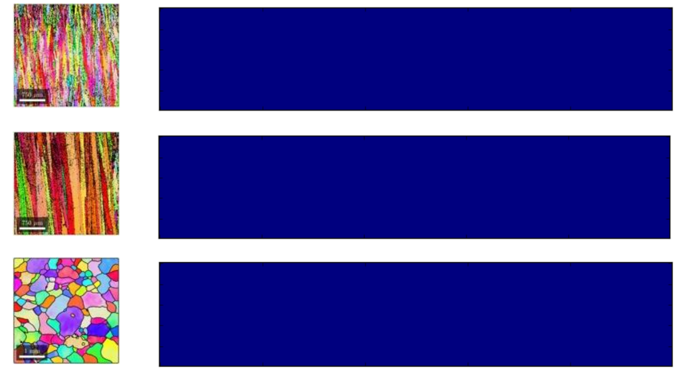


Data Driven Microstructure Development

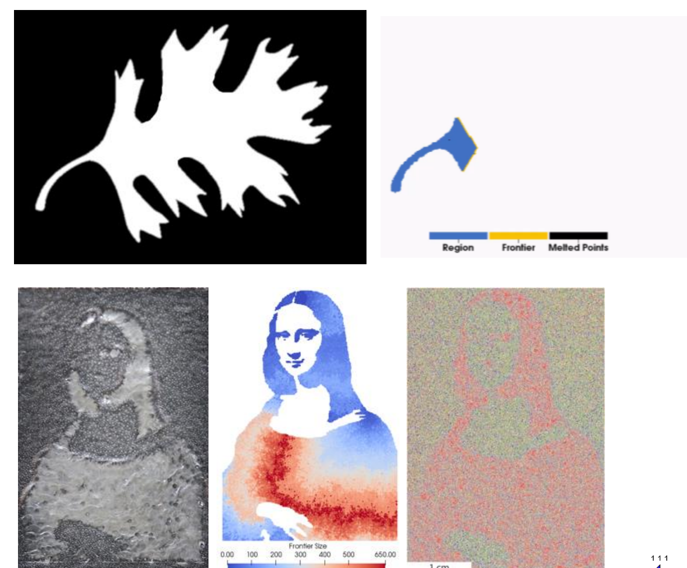
Fatigue-resistant Hybrid microstructure Components



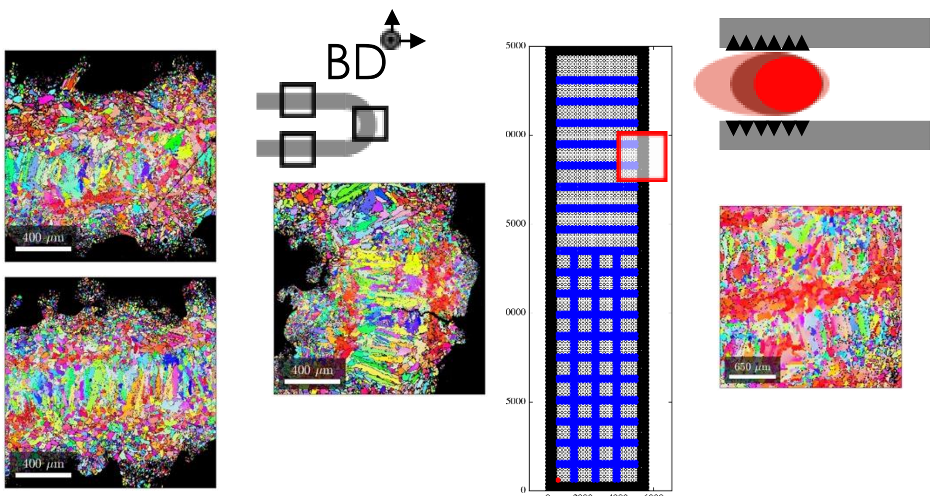
Point Heat Source Control for Structure Control

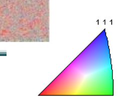


AI Driven Scan Algorithms

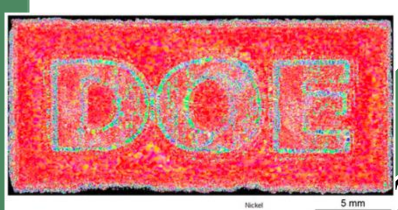


Localized Conductive Solidification Manipulation



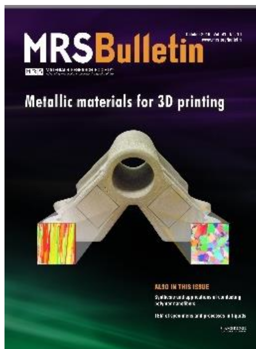


Future of Data Driven Scan Strategies



2015

Demonstration

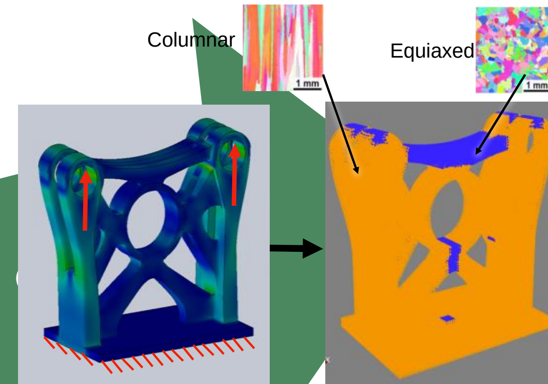


2016-2018

Engineered Scan Strategies

2019

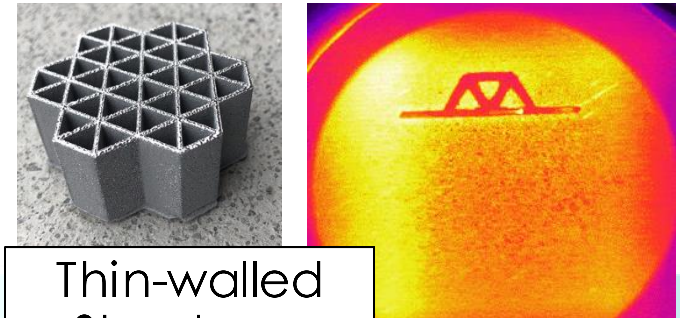
AI Informed Scan Strategies



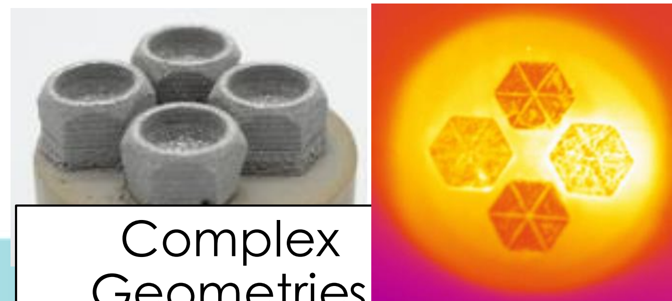
Future

Microstructure Optimized Components

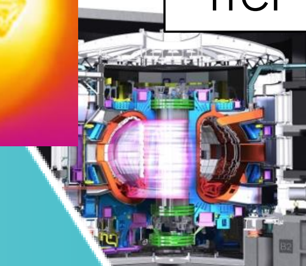
AM of Refractory Metals for Extreme Environments



Thin-walled Structures



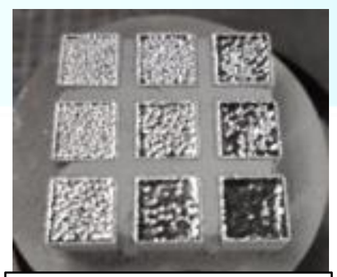
Complex Geometries



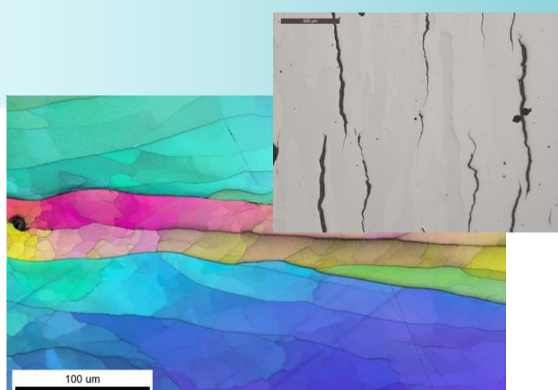
iter

- Next-generation nuclear energy will require components from hard-to-manufacture refractories

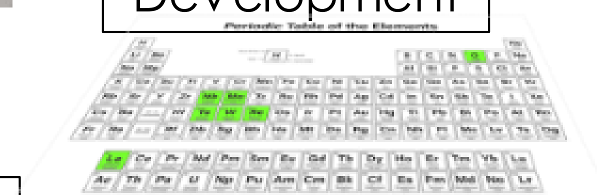
TCR



Parameter Development

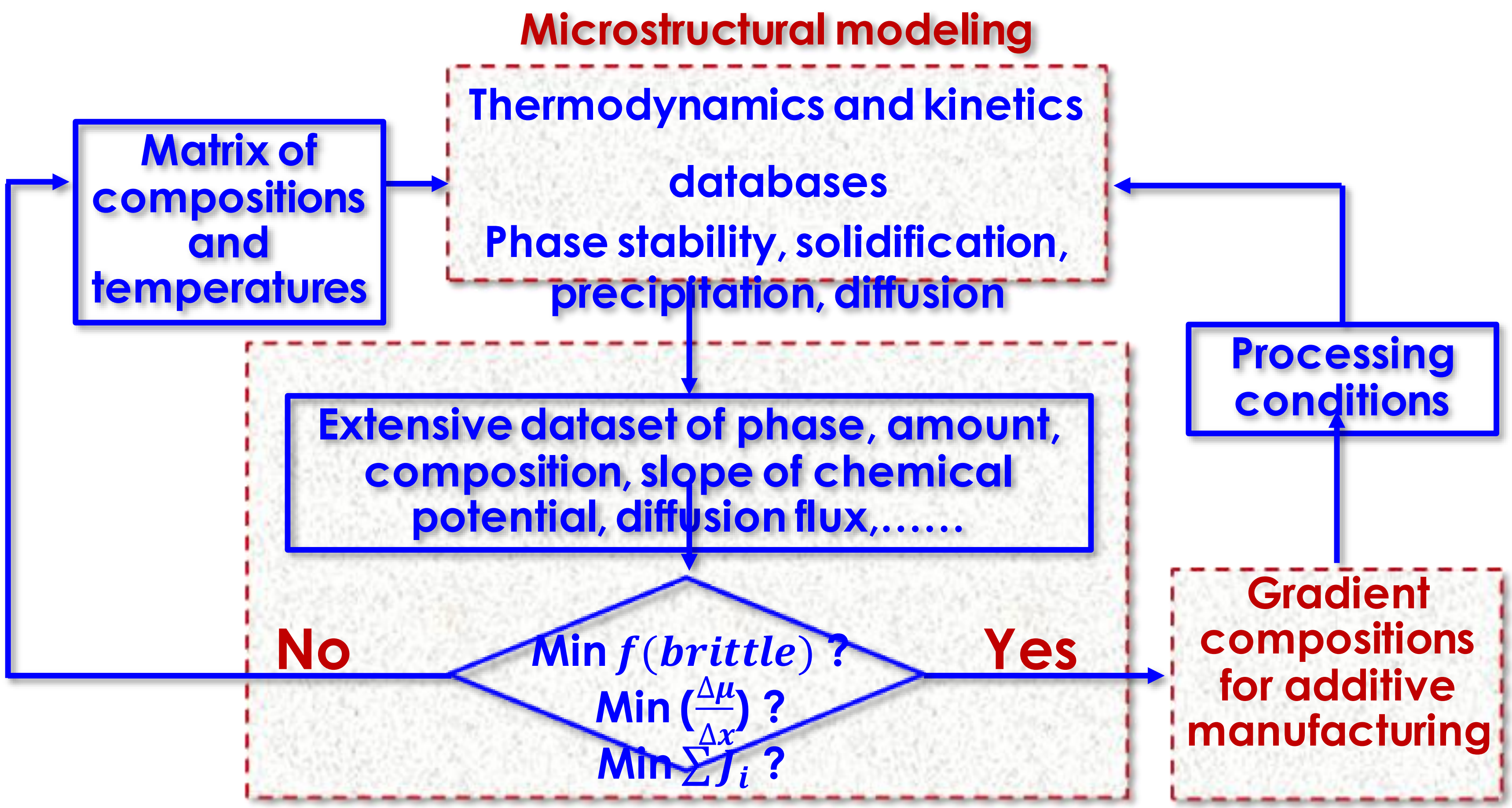


Eliminating Cracking and Porosity

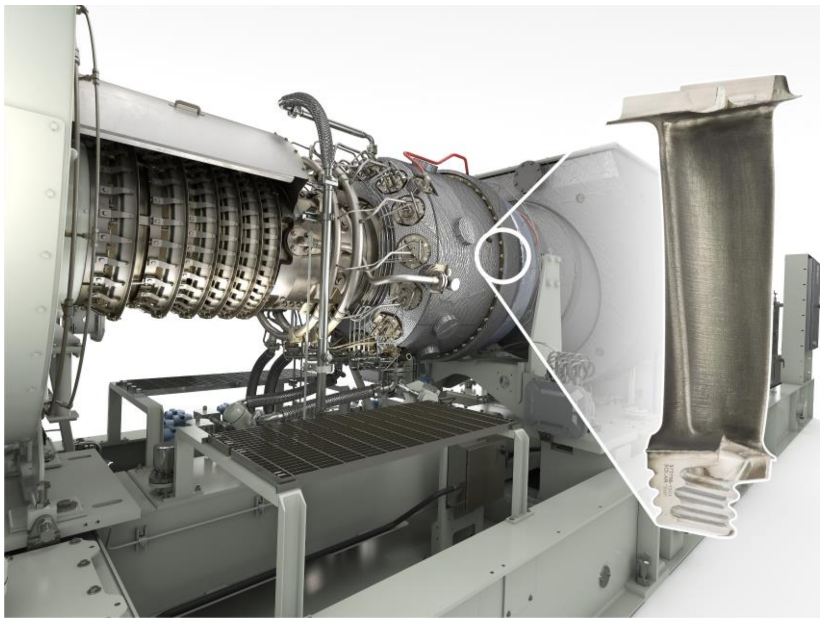


Alloy Development

Integrating Materials Design with Process Optimization for Additive Manufacturing



Summary



- Physical Processes of AM: Many of the physics, heat and mass transfer, solidification and solid-state transformations are the same as welding and joining with complex boundary conditions.
- Challenges: Defect formation and microstructural heterogeneities are affected by interaction between geometry, process, and alloy chemistry!
- Current Directions: Fusion based AM has been demonstrated as a reliable technology for fabricating non-weldable Ni-base superalloys for critical rotating applications.
- Opportunities: AM allows for site-specific control of microstructure in Ni-base alloys through thermal management, phase stability and kinetics, even in complex geometries. Extendable to refractory materials